AD-781 113

ON THE UNIQUENESS OF THE SHAPLEY VALUE

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Prepared for:

Office of Naval Research

June 1974

AD-781113

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Cornell University Department of Operations Research Ithaca, New York 14850	Unclassified
	2b. GROUP

3. REPORT TITLE

ON THE UNIQUENESS OF THE SHAPLEY VALUE

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Report

5. AUTHOR(S) (Last name, first name, initial)

Pradeep Dubey

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1974	19	3

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
N00014-67-A-0077-0014, task Nr 047-094	
b. PROJECT NO.	Technical Report
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. AVAILABILITY/LIMITATION NOTICES

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Operations Research Program Office of Naval Research Arlington, Virginia 22217

13. ABSTRACT

L.S. Shapley [Shapley, 1953] showed that there is a unique value defined on the class D of all superadditive cooperative games in characteristic function form (over a finite player - set N) which satisfies certain intuitively plausible axioms. Moreover, he raised the question whether an axiomatic foundation could be obtained for a value (not necessarily the Shapley value) in the context of the subclass C (respectively C', C'') of simple (respectively simple monotonic, simple superadditive) games alone. This paper shows that it is possible to do this.

Theorem I gives a new simple proof of Shapley's theorem for the class G of all games (not necessarily superadditive) over N. The proof contains a procedure for showing that the axioms also uniquely specify the Shapley value when they are restricted to certain subclasses of G, e.g., C. In addition it provides insight into Shapley's theorem for D itself.

Restricted to C' or C'', Shapley's axioms do not specify a unique value. However it is shown in theorem II that with a reasonable variant of one of his axioms a unique value is obtained and, fortunately, it is just the Shapley value again.

14		LINK A		LINK B		LINK C	
	KEY WORDS	ROLE	WT	ROLE	WT	ROLE	WT
Shapley value Superadditive cooperative games in characteristic function form Monotonic simple games Minimal winning coalition							

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TECHNICAL REPORT

ON THE UNIQUENESS OF THE SHAPLEY VALUE*

by

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June, 1974

Notation

For a set S we denote by $|S|$ the number of elements that S contains and frequently write it as s; similarly t abbreviates $|T|$ for a set T, etc. 2^S denotes the class of all subsets of the set S. $\emptyset$ stands for the empty set. R, as usual, represents the real line and Z^+ the set of positive integers. For a vector v in R^n, v_i is the ith component of v. The symbol i is used both as a number and as the name of a player in N, but its meaning will be clear from the context.

1. <u>INTRODUCTION</u>. An n-person cooperative game in characteristic function <u>form</u> is a pair (N,v) where $N = (1,2,\ldots,n)$ is a set of n players; and v is a function

$$v: \quad 2^N \to R$$

with the property $v(\emptyset) = 0$. Intuitively $v(S)$ represents the "worth" ("value", "power") of the coalition S of players, i.e., the least payoff that S can guarantee itself no matter what the other players (that are not in S) do. Given a game v it is desirable to have a measure of the apriori "value" of each player in v.

Denote the class of all games on N by G.

Let ϕ be a function

$$\phi: \quad G \to R^n$$

which we interpret as follows: $\phi_i(v)$ is the <u>value</u> of the ith player in the game v.

Shapley proposes three axioms which the function ϕ ought to satisfy. In order to state them it is necessary to first define a few concepts. All games in the definitions below are assumed to be in G.

1. S is called a <u>carrier</u> for v if

$$v(T) = v(T \cap S) \text{ for all } T \subseteq N.$$

2. If $\pi: N \to N$ is a permutation of N, then the game πv is defined by

$$\pi v(T) = v(\pi(T)) \text{ for all } T \subseteq N.$$

3. Given any two games v_1 and v_2, the game $v_1 + v_2$ is defined by

$$(v_1 + v_2)(T) = v_1(T) + v_2(T) \text{ for all } T \subseteq N.$$

Shapley's axioms are:

S1. If S is any carrier for v, then $\sum_{i \in S} \phi_i (v) = v(S)$.

S2. For any permutation π and $i \in N$,

$$\phi_{\pi(i)}(\pi v) = \phi_i(v)$$

S3. If v_1 and v_2 are any games, then

$$\phi(v_1 + v_2) = \phi(v_1) + \phi(v_2).$$

Shapley proved the following

Theorem I. There is a unique function ϕ, defined on G, which satisfies the axioms S1, S2, S3.

Proof. For each coalition S define the game $v_{S,c}$ by

$$v_{S,c}(T) = \begin{cases} 0 & \text{if } S \not\subset T \\ c & \text{if } S \subset T. \end{cases}$$

Then it is clear that S and its supersets are all carriers for $v_{S,c}$. Therefore, by S1,

$$\sum_{i \in S} \phi_i (v_{S,c}) = c, \quad \text{and}$$

$$\sum_{i \in S \cup \{j\}} \phi_i(v_{S,c}) = c \quad \text{whenever } j \notin S$$

This implies that $\phi_j(v_{S,c}) = 0$ whenever $j \notin S$. Also if π is a permutation of N which interchanges i and j (for any $i \in S$ and $j \in S$ and leaves the other players fixed, then it is clear that $\pi v_{S,c} = v_{S,c}$ and thus, by S2,

$$\phi_i(v_{S,c}) = \phi_j(v_{S,c}) \quad \text{for any } i \in S \text{ and } j \in S.$$

Therefore $\phi(v_{S,c})$ is unique, if ϕ exists, and is given by

$$\phi_i(v_{S,c}) = \begin{cases} c/|S| & \text{if } i \in S \\ 0 & \text{if } i \notin S \end{cases}$$

Now the games $\{v_{S,c} \mid \emptyset \neq S \subset N, \; c \in R\}$ form an additive basis for the vector space G, and a proof of the theorem could be obtained by showing this [Shapley, 1953]. However, for our purposes, it is useful to consider the games $\{v'_{S,c} \mid \emptyset \neq S \subset N, \; c \in R\}$ defined by

$$v'_{S,c}(T) = \begin{cases} c & \text{if } T = S \\ 0 & \text{if } T \neq S. \end{cases}$$

Any game v can be written as a finite sum of games of the type $v'_{S,c}$. Hence the uniqueness of ϕ follows, using S3, if we can show that each $\phi(v'_{S,c})$ is unique.

Assume that $\phi(v'_{S,c})$ is unique for $|S| = k + 1, \ldots, n$. (This is obviously true for $|S| = n$ because $v'_{N,c} = v_{N,c}$.) We will then show that $\phi(v'_{S,c})$ is unique for $|S| = k$.

Let $S_1, \ldots, S_\ell$ be all of the proper supersets of S. Note that $|S_i| > k$ for $i = 1, \ldots, \ell$, thus $\phi(v'_{S_i,c})$ is unique by the inductive assumption.

$$\text{But} \quad v_{S,c} = v'_{S,c} + v'_{S_1,c} + \cdots\cdots\cdots + v'_{S_\ell c}$$

$$\text{Therefore, by S3,} \quad \phi(v_{S,c}) = \phi(v'_{S,c}) + \phi(v'_{S_1,c}) + \ldots + \phi(v'_{S_\ell,c}) \qquad (1)$$

Since all the terms except $\phi(v'_{S,c})$ are unique, so is $\phi(v'_{S,c})$. This concludes the proof that ϕ, if it exists, is unique.

The proof of uniqueness has implicit in it, as was to be expected, a recipe for constructing ϕ. Suppose

$$\phi_i(v'_{S,c}) = \frac{(s-1)!(n-s)!}{n!} \cdot c \quad \text{if } i \in S$$

$$- \left(\frac{s}{n-s}\right)\frac{(s-1)!(n-s)!}{n!} \cdot c \quad \text{if } i \notin S.$$

for $s = |S| = k + 1, \ldots, n$. This is obviously true for $|S| = n$ since

$v'_{.l,c} = v_{il,c}$. It follows, using (1), that

$$\phi_i(v'_{S,c}) = \frac{(s-1)!(n-s)!}{n!} \cdot c \quad \text{if} \quad i \epsilon S$$

$$-\left(\frac{s}{n-s}\right) \cdot \frac{(s-1)!(n-s)!}{n!} c \quad \text{if} \quad i \notin S$$

for $|S| = k$.

It is now straightforward to obtain $\phi(v)$ for any v.

Since $v = \sum_{\emptyset \neq S \subset N} v'_{S,v(S)}$

$$\phi(v) = \sum_{\emptyset \neq S \subset N} \phi(v'_{S,v(S)}) \quad \text{by} \quad S3.$$

The right-hand-side, when simplified, gives

$$\phi(v) = \sum_{\{i \epsilon T \subset N\}} \frac{(t-1)!(n-t)!}{n!} \quad v(T) - v(T-\{i\}) \ ,$$

Shapley's familiar formula. It is easy to verify that ϕ, defined as above, satisfies the axioms S1, S2, S3. This completes the proof of theorem I.

2. <u>UNIQUENESS FOR SUBCLASSES</u>   One can restrict S1, S2, S3 to subclasses K of G. S2 is then required to hold only if $\pi v \epsilon K$ whenever $v \epsilon K$, and S3 only if $v_1 + v_2 \epsilon K$ whenever $v_1 \epsilon K$ and $v_2 \epsilon K$. The question arises whether the axioms, so restricted, specify a unique ϕ on K. That they specify at least one ϕ is clear by considering the restriction of the Shapley value on G to K. By following the procedure given in the above proof we can establish the uniqueness of ϕ for certain K. It needs to be emphasized that <u>in each case</u> the proof of the uniqueness of ϕ on K is given by a recursive construction of ϕ on K which parallels the construction in the proof of theorem I. (The case $K = D$ requires a somewhat special treatment which is outlined below). Therefore it is <u>not</u> necessary to turn to ϕ on G and restrict its domain to K in order to prove the existence of ϕ on K.

The case $K = D$. D is the subclass of G which consists of all <u>superadditive</u> <u>games</u> in G, i.e., games v in G for which $v(S \cup T) \geq v(S) + v(T)$ whenever $S \cap T = \emptyset$. Though Shapley's proof in [Shapley 1953] is also a proof of theorem I, it is essentially concerned with D, which is perhaps why games of the type $v'_{S,c}$ are not considered in it. (Recall that $v'_{S,c}$ is not in D if $S \neq N$). However $\{v'_{S,c} \mid \emptyset \neq S \subset N, c \in R\}$ does help one to construct Shapley's proof also. We first show that $\{v_{S,c} \mid \emptyset \neq S \subset N, c \in R\}$ forms a basis for G. Suppose that $v'_{S,1}$ is in the linear span of $\{v_{T,1} \mid T$ is a superset of $S\}$ when $|S| = k+1, \ldots n$. This is trivially true for $|S| = n$ because, as we have remarked before, $v_{N,c} = v'_{N,c}$. Let $|S^*| = k$. Since

$$v'_{S^*,1} = v'_{S,1} - v'_{S^*_1,1} - \ldots - v'_{S^*_j,1} \tag{2}$$

where $S^*_1, \ldots, S^*_j$ are all the proper supersets of S^*, and since by the inductive assumption each $v'_{S^*_1,1}$ is in the linear span of $\{v_{T,1} \mid T$ is a superset of $S^*_i\}$, it follows that $v'_{S^*,1}$ is in the linear span of $\{v_{T,1} \mid T$ is a superset of $S^*\}$. From the fact that $\{v'_{S,1} \mid \emptyset \neq S \subset N\}$ spans G, we now wee that $\{v_{S,1} \mid \emptyset \neq S \subset N\}$ also spans G. It is in fact a basis for G because it has the same number of elements as $\{v'_{S,1} \mid \emptyset \neq S \subset N\}$ which is well known to be a basis.

Express a v in D <u>uniquely</u> as: $v = \sum c_S v_{S,1}$. Some of the c_S on the right hand side may be negative so that the equation may contain games that are not in D. This would prevent an application of S3 which is restricted to D. To overcome this, transpose terms with negative c_S coefficients to the left. Then it is easy to see that the new equation will only contain games that are in D. An application of S3 now proves the uniqueness of ϕ on D. To find c_S explicitly, first express each $v'_{S,1}$ in terms of the basis $\{v_{S,1} \mid \emptyset \neq S \subset N\}$ using (2) and induction, and then substitute into

$v = \sum\limits_{\emptyset \neq T \subset N} v'_{T,v(T)}$. It can be shown in this way that $c_S = \sum\limits_{T \subset S} (-1)^{s-t} v(T)$, which of course enables us to write out an explicit formula for $\phi(v)$ as is done in [Shapley, 1953]. This is not simple, however, and it is easier to show the existence of ϕ on D by restricting the previously obtained ϕ on G to D.

Others cases, $K \neq D$. In the following examples (which are by no means exhaustive) the proof of the uniqueness of ϕ on the given K is completely parallel to the proof of theorem I, and involves a similar recursive construction of ϕ.

A. The subclass of all simple games, i.e., all games v for which $v(S) = 0$ or 1, for any $S \subset N$.

B. The subclass of all games v for which $v(S) = 0$ whenever $|S| \leq k$; as well as the subclass of all simple games with this restriction.

C. The subclass of all games v in which certain players $i_1, \ldots, i_k$ are distinguished and $v(S) = 0$ if $\{i_1, \ldots, i_k\} \not\subset S$; as well as the subclass of all simple games with this restriction.

Remarks. (I). The convex cone generated by the simple games with veto players (i.e., players i such that $v(S) = 0$ if $i \notin S$, for all $S \subset N$) is the subclass L of all games with non-empty cores [Spinneto, 1971]. Therefore case C shows that the axioms uniquely specifiy the Shapley value on L. In fact this is true for convex cones generated by the class of games in any one of A, B, or C or their unions.

(II). For any $P \subset G$, $|P| < \infty$, we can determine in a finite number of steps whether or not the axioms uniquely specify the Shapley value on P; and if they do not, we can construct different ϕ's on P which satisfy the axioms. Indeed, this corresponds to checking whether a certain system of linear equations has a unique solution or not. The size of this system can be cut down

using a procedure which mimics the proof of theorem I. (We omit the details.)

3. **MONOTONIC SIMPLE GAMES**   Let C' be the subclass of all monotonic simple games in G, i.e., simple games v for which $v(S) = 1$ implies that $v(T) = 1$ whenever $S \subset T$. And let C'' be the subclass of all superadditive simple games in G.

The axioms S1,S2,S3 do not uniquely specify the Shapley value on C' or C'' if $|N| > 2$. First note that the games in C' or C'' for which the value is determined by S1 and S2 alone are precisely of the type $v_{S,1}$. Pick a game v in C'' (and thus also in C' since $C'' \subset C'$) which is not of the type $v_{S,1}$. An example of one is:

$$v(N-\{i\}) = v(N-\{j\}) = v(N) = 1, \quad \text{and}$$

$$v(S) = 0 \quad \text{for all other } S \subset_N \quad .$$

where i and j are any two distinct players in N, and where we assume that $|N| > 2$.

Set $\phi_i(v) = \phi_j(v) = p$, where p is an arbitrary real number, and set

$$\phi_k(v) = \frac{1-2p}{|N - \{i,j\}|} \quad \text{for } k \neq i,j.$$

Then it is obvious that $\phi(v)$ satisfies S1 and S2. It also satisfies S3 vacuously. For suppose $v + v' = v''$ for a $v' \varepsilon C'$ and a $v'' \varepsilon C'$. Then $v(N) + v'(N) = v''(N)$. But $v(N) = 1$, therefore $v''(N) = 1$, which implies that $v'(N) = 0$. Thus $v' = 0$ since v' is monotonic. Also, if $v - v' = v''$ for a $v' \varepsilon C'$ and a $v'' \varepsilon C'$, then two cases arise: (a) $v''(N) = 1$, therefore $v'(N) = 0$, and so $v' = 0$. (b) $v''(N) = 0$ which implies that $v'' = 0$, and hence $v' = v''$. There is no question, therefore, of S3 being violated for any choice of p, and so ϕ is not uniquely specified on C' or C'' by S1,S2,S3.

However, if we replace $S3$ by a variant of it, $S3'$ (which will be stated below), then a unique ϕ is specified on C' or C'' and it is just the Shapley value.

In what follows we will write out only the case for C'', because the case for C' is obtained by replacing C'' by C' throughout.

First we make a few definitions. For $v \epsilon C''$ and $v' \epsilon C''$ let $v \vee v'$ denote the game given by

$$(v \vee v')(S) = \begin{cases} 1 & \text{if either } v(S) = 1 \text{ or } v'(S) = 1 \\ 0 & \text{if } v(S) = 0 \text{ and } v'(S) = 0. \end{cases}$$

Note that $v \vee v'$ may not always be in C'' for a v in C'' and a v' in C''. (However $v \vee v'$ is in C' whenever v is in C' and v' is in C'.). Let $v \wedge v'$ denote the game given by

$$(v \wedge v')(S) = \begin{cases} 1 & \text{if } v(S) = 1 \text{ and } v'(S) = 1 \\ 0 & \text{if } v(S) = 0 \text{ or } v'(S) = 0. \end{cases}$$

Let us make a simple check to see that $v \wedge v' \epsilon C''$ whenever $v \epsilon C''$ and $v' \epsilon C''$. If $v \wedge v' \not\epsilon C''$, then there are coalitions S and T, $S \cap T = \emptyset$, such that $(v \wedge v')(S \cup T) < (v \wedge v')(S) + (v \wedge v')(T)$. But by the definition of $v \wedge v'$ this means that either $v(S \cup T) < v(S) + v(T)$ or $v'(S \cup T) < v'(S) + v'(T)$, which is a contradiction. (A similar argument shows that C' is closed under $\wedge$).

We are now in a position to state $S3'$:

$S3'$. If $v \vee v' \epsilon C''$ whenever $v \epsilon C''$ and $v' \epsilon C''$ then

$$\phi(v \vee v') + \phi(v \wedge v') = \phi(v) + \phi(v').$$

(In stating $S3'$ for C' we may drop the "if" because $v \vee v' \epsilon C'$ always.)

Theorem II. There is a unique function ϕ, defined on C'', which satisfies the axioms $S1, S2, S3'$. Moreover, this ϕ is just the Shapley value.

Proof. Every v in C'' has a finite number of minimal winning coalitions $S_1, \ldots, S_k$, i.e. coalitions S_i such that $v(T) = 1$ if $S_i \subset T$ for some i and $v(T) = 0$ if $S_i \not\subset T$ for all i. Clearly

$$v = v_{S_1,1} \vee v_{S_2,1} \vee \cdots \vee v_{S_k,1}$$

where the right hand side is defined associatively. Let $n^1(v) = \min \{p \in Z^+ |$ there exists a minimal winning coalition T of v such that $|T| = p\}$ and let $n^2(v) =$ the number of minimal winning coalitions T of v such that $|T| = n^1(v)$.

The proof of the uniqueness of ϕ will be by induction on $n^1(v)$ and $n^2(v)$.

For $n^1(v) = n, v = v_{N,1}$, in which case $\phi(v)$ is obviously unique.

Lemma I. Suppose $\phi(v)$ has been shown to be unique for all v such that $n^1(v) = k+1, k+2, \ldots, n$. Then $\phi(v)$ is unique when $n^1(v) = k$ <u>and</u> $n^2(v) = 1$.

Proof. Let S be the unique minimal winning coalition with k players. If S is the only minimal winning coalition of v, then $v = v_{S,1}$ and $\phi(v)$ is unique. Otherwise let $S_1, \ldots, S_m$ denote all of the minimal winning coalitions of v apart from S.

<u>Note:</u> $|S_i| > k$ for $1 \le i \le m$ since $n^2(v) = 1$. Now

$$(v_{S_1,1} \vee v_{S_2,1} \vee \cdots \vee v_{S_m,1}) \vee v_{S,1} = v$$

say, $v' \vee v_{S,1} = v$

It follows that $n^1(v') > k$. Therefore $\phi(v')$ is unique by the inductive

assumption. Further, $n^1(v_{S,1} \wedge v') > k$. This is obvious from the definition of $\wedge$. Therefore $\psi(v \wedge v')$ is also unique by the inductive assumption. Invoke axiom $S3'$. Then

$$\phi(v) = \phi(v' \vee v_{S,1}) = \psi(v') + \psi(v_{S,1}) - \phi(v_{S,1} \wedge v')$$

Since all the three vectors on the right hand side are unique, so is $\phi(v)$.

Lemma II. Suppose $\psi(v)$ has been shown to be unique for all v such that either

$$n^1(v) = k + 1, \ldots, n \tag{3}$$

$$\text{or} \quad n^1(v) = k \quad \underline{\text{and}} \quad n^2(v) = 1, \ldots, j \tag{4}$$

Then $\phi(v)$ is unique when $n^1(v) = k$ $\underline{\text{and}}$ $n^2(v) = j + 1$.

Proof: Let $S_1, \ldots, S_{j+1}$ be the minimal winning coalitions of v with k players each. And let $T_1, \ldots, T_m$ be all the other minimal winning coalitions of v. By the conditions on $n^1(v)$ and $n^2(v)$ it is clear that $|T_i| > k$ for $1 \leq i \leq m$. Now

$$(v_{T_1,1} \vee \cdots \vee v_{T_m,1} \vee v_{S_1,1} \vee \cdots \vee v_{S_j,1}) \vee v_{S_{j+1},1} = v.$$

$$\text{say,} \quad v'' \vee v_{S_{j+1},1} = v$$

clearly v'' satisfies (4) and $v'' \wedge v_{S_{j+1},1}$ satisfies (3). Therefore $\phi(v'')$ and $\phi(v'' \wedge v_{S_{j+1},1})$ are both unique by the inductive assumption. By $S3'$,

$$\phi(v) = \phi(v'' \vee v_{S_{j+1},1})$$

$$= \phi(v'') + \phi(v_{S_{j+1},1}) - \phi(v'' \wedge v_{S_{j+1},1})$$

which proves the uniqueness of $\phi(v)$.

Putting together lemmas I and II we get that $\phi(v)$ is unique for any feasible numbers $n^1(v)$ and $n^2(v)$, i.e., for all $v \epsilon C''$, which concludes the proof of the theorem.

It is clear that the Shapley value ϕ on G satisfies $S1, S2, S3'$ when it is restricted to C''. Indeed $v + v' = (v \vee v') + (v \wedge v')$ where we regard the $+$ as taking place in the vector space G. Hence by $S3$ $\phi(v) + \phi(v') = \phi(v \vee v') + \phi(v \wedge v')$. Thus the Shapley value is <u>the</u> unique ϕ on C'' which satisfies $S1, S2, S3'$.

However, we need not depend on the ϕ already defined on G to establish the existence of ϕ on C''. It is quite clear that implicit in the proof of uniqueness is a recursive construction of ϕ. (We omit this because it is straightforward.)

<u>Remarks</u>: (III)   Theorem II holds when we replace C' (respectively C'') by certain subclasses of C' (respectively C''). The proofs are similar and involve stopping the induction at appropriate stages, and considering games that take on values in $\{c,0\}$ instead of $\{1,0\}$. We give just two examples: Subclasses of C' (or C'') for which (1) $v(S) = 0$ if $|S| \leq k$, (2) $v(S) = 0$ if $\{i_1, \ldots i_k\} \not\subset S$.

(IV) Let F be the class of all monotonic simple games which do not have "ties", i.e., games v for which $v(S) = 1$ if and only if $v(N \backslash S) = 0$. (This class contains the class of all weighted majority games for which the quota is greater than half the total weight.) By changing $S1$, but retaining $S2$ and $S3'$, we can obtain an axiomatic foundation for the Banzhaf value in its unnormalized form (Lucas, 1973) when it is restricted to F. Further, we can redefine the Banzhaf value on $C' \backslash F$ in a reasonable way so that the

same axioms specify this extended function on C' also. The proof of this is similar to the proof of theorem II, and will appear in a forthcoming paper.

The above statements hold if we replace "monotonic" by "superadditive" and "C'" by "C''" throughout.

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